Digital Elevation Model of Hilo, Hawaii:
Procedures, Data Sources and Analysis

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1. INTRODUCTION

In August of 2011, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Hilo, Hawaii (Fig. 1). A 1/3 arc-second[1] DEM referenced to mean high water (MHW) was carefully developed and evaluated. The 1/3 arc-second MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Figs. 2, 5 and 6). The DEM will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Hilo DEM.
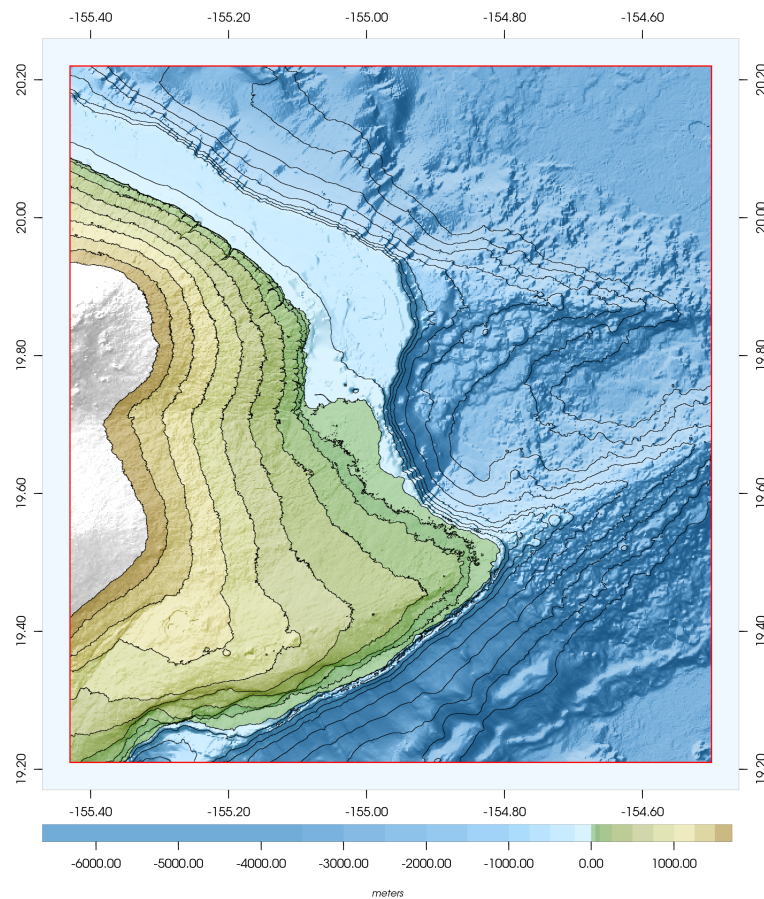
Figure 1. *Shaded relief image of the Hilo DEM.*

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[1] The Hilo, HI DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Hilo Bay, HI, 1/3 arc-second of latitude is equivalent to 10.256 meters; 1/3 arc-second of longitude equals 9.347 meters

2. STUDY AREA

The Hilo DEM covers the area surounding Hilo Bay (Figure 2). The DEM represents an area located on the island of Hawaii in the state of Hawaii, and includes the town of Hilo, which is the largest settlement on the island of Hawaii and the second largest settlement in the State of Hawaii.

Table 1. Specifications for the Hilo DEM

Grid Area	Hilo, Hawaii
Coverage Area	-155.43 °, 20.22 °, -154.5 °, 19.21 °
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum of 1983 (NAD 83)
Vertical Datum	MHW
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid
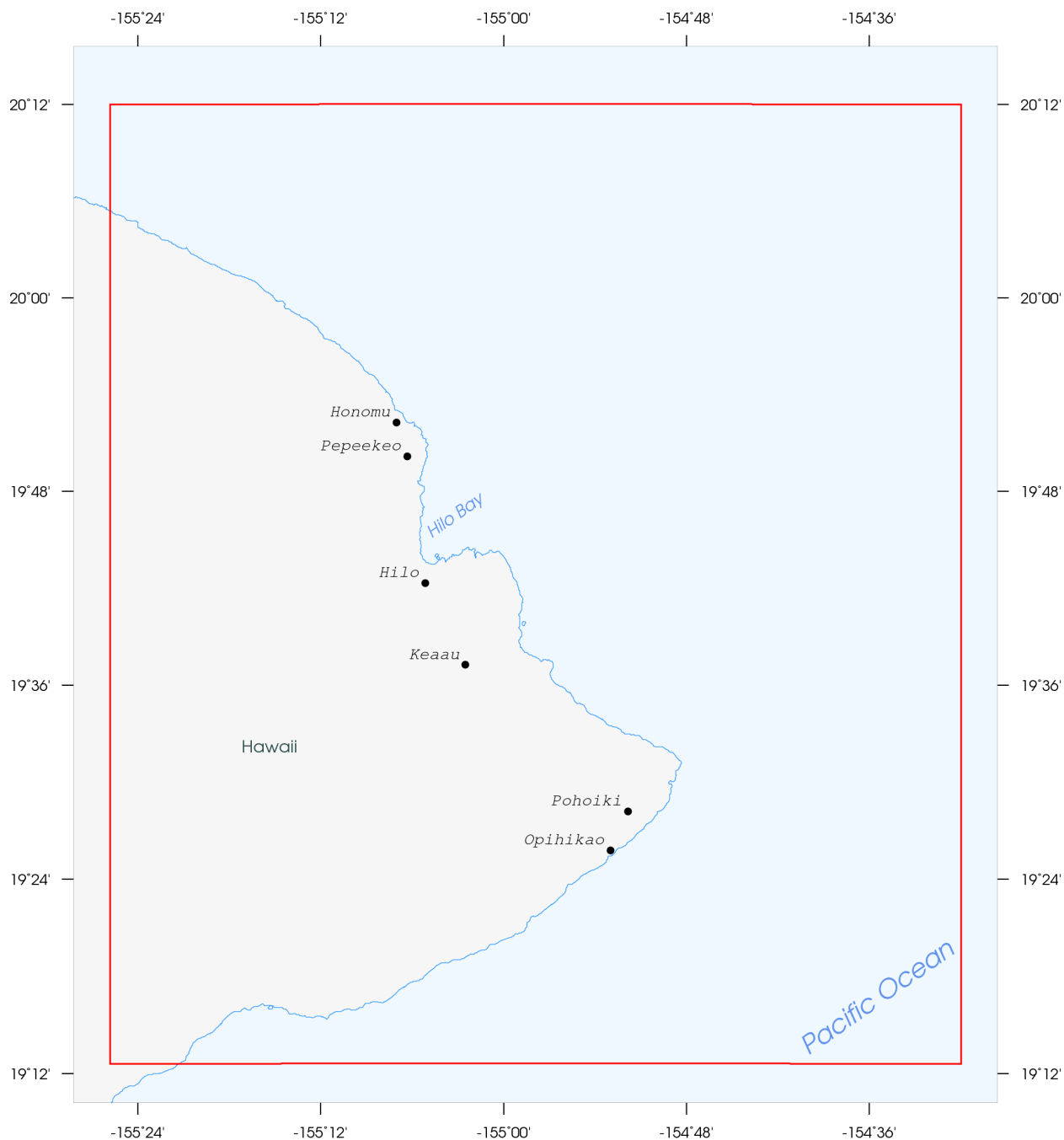
Figure 2. *Extents of the Hilo DEM, shown in red, and surounding area*

3. SOURCE ELEVATION DATA

The best freely available digital data were obtained by NGDC from several U.S. federal agencies: NOAA's NGDC, Office of Coast Survey (OCS) and Coastal Services Center (CSC). Data were gathered in an area slightly larger (∼5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

3.1   Data Sources And Processing

Coastline, bathymetric, and topographic digital datasets (Tables 2, 3 and 4) were obtained by NGDC and shifted to common horizontal and vertical datums: NAD 83 geographic[2] and MHW, respectively. The datasets were assessed to determine data quality and were manually edited where needed. Vertical datum transformations to MHW were accomplished using a constant offset obtained from tide station values located at Hilo Bay (see Table 5).

3.1.1   *Coastline*

Coastline datasets of the Hilo Bay region were obtained from a variety of sources. The main dataset used in developing a combined, detailed coastline was the zero-line contour extracted from the USGS NED datasets (Table 2, Figure 3). This dataset provided a detailed MHW coastline of the Hilo Bay region. NGDC evaluated but did not use the NOAA Office of Coast Survey (OCS) coastline.

The zero-line contour coastline was edited by NGDC using ESRI World Imagery to better represent the coastline immediately sourrounding Hilo Bay (Fig. 3) and to ensure the resolution of the breakwater in Hilo Bay, which was not adequately represented in other data sources (Fig. 4).

Table 2. Shoreline datasets used in compiling the Hilo DEM

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Coordinate System	URL
NGDC	2011	Composite vectorized hydraulic breaklines	Not defined	NAD 83 geographic	MHW	N/A
NGDC	2011	Digitized vector Coastline	Not defined	WGS 84 geographic	MHW	N/A

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[2]The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.
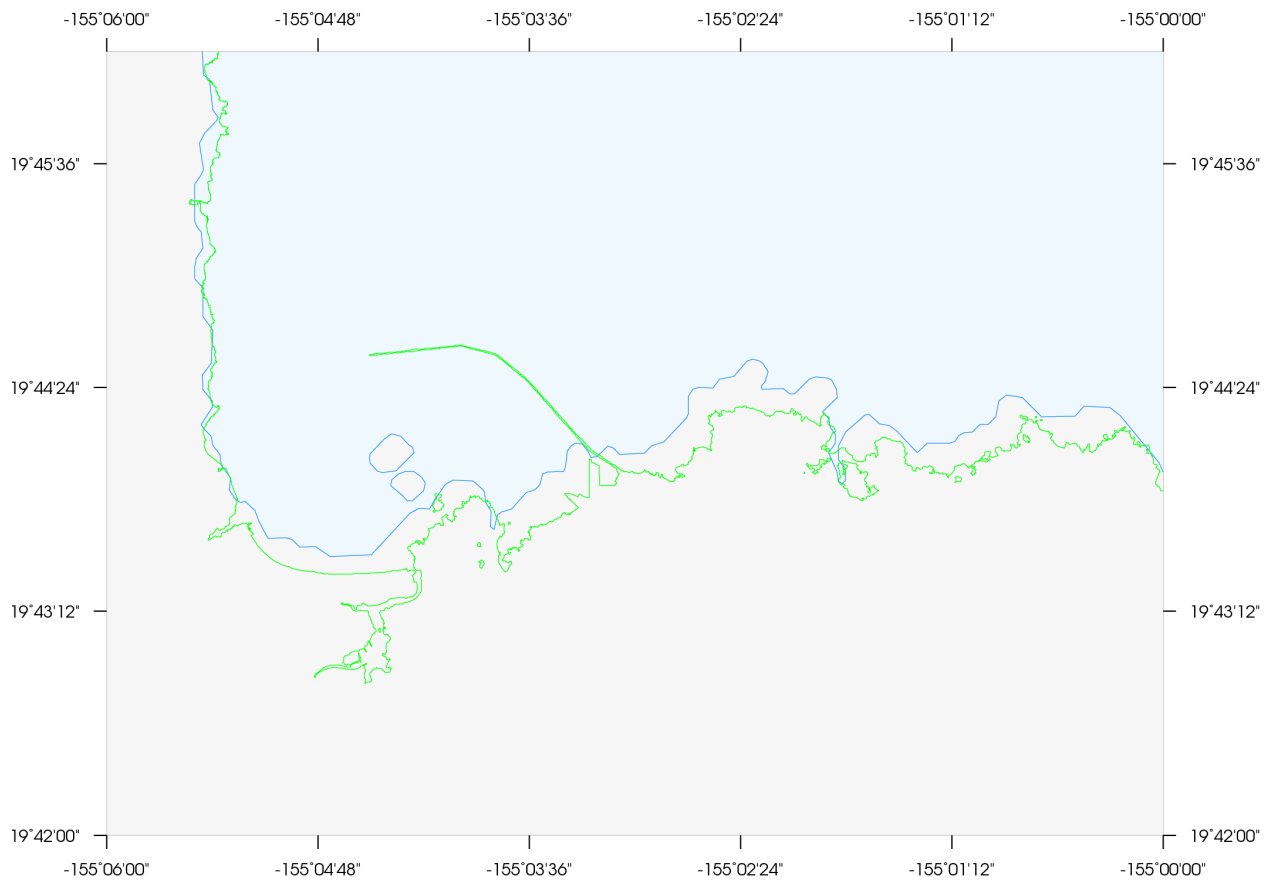
Figure 3. *Sample of Hilo Bay where NGDC digitized the coastline to aerial imagery; digitized coastline shown in green, vectorized hydraulic breaklines shown in blue.*

Figure 4. *Aerial image of Hilo Harbor, showing the breakwater extending into the bay. Image courtesy of United States Army Corps of Engineers (USACE) http://www.poh.usace.army.mil/CW/CWPhotos-HIHI.htm*

3.1.2   Bathymetry

Bathymetric datasets available in the Hilo region included 31 NGDC multibeam sonar surveys and 1 Electronic Nautical Chart (ENC) that was available from OCS (Table 3; Figure 5). NGDC evaluated but did not use the NOAA NOS hydrographic dataset due to conflicts with the Multibeam surveys.

Table 3. Bathymetric datasets used in compiling the Hilo DEM

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Coordinate System	URL
NGDC	2011	Multibeam soundings	N/A	NAD 83 geographic	Assumed mean sea level (MSL)	http://www.ngdc. noaa.gov/mgg/ bathymetry/ multibeam.html
OCS	2010	Extracted points from ENC	Ranges from 1:20,000 to 1:458,596 (varies by chart)	WGS84 geographic	mean lower low water (MLLW)	http://www. nauticalcharts. noaa.gov
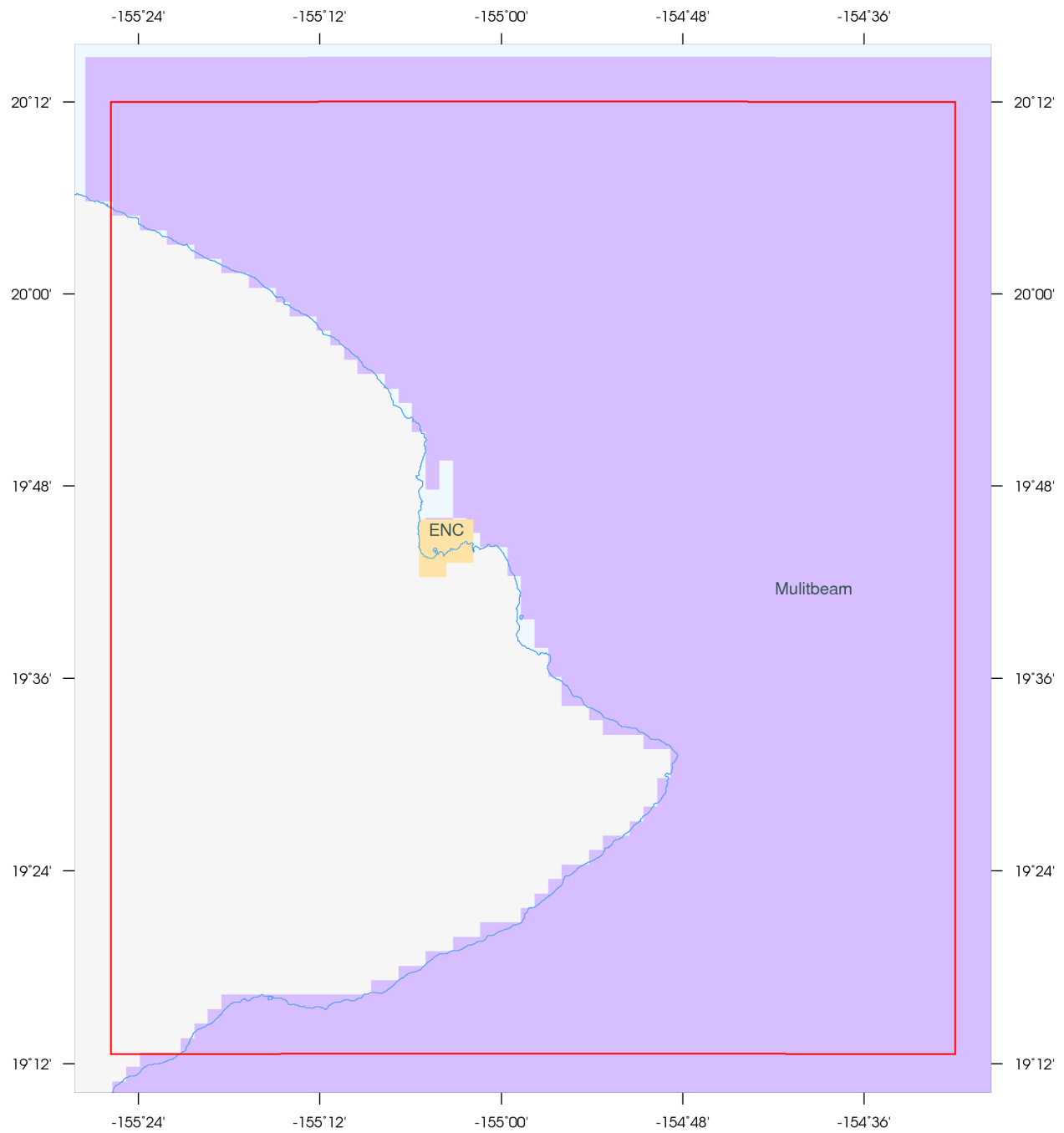
Figure 5. *Bathymetric data sources in the Hilo region.*

1) NGDC Multibeam

Thirty-one multibeam swath sonar surveys were available from the NGDC multibeam database for use in the development of the Hilo DEM (Fig. 5). This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. All surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be equivalent to MSL. The data were gridded to 1 arc-second resolution using MB-System and xyz data were extracted and transformed to MHW using a constant offset.

2) OCS Electronic Navigational Charts

One ENC was available from OCS in the Hilo Bay coverage area. The ENC was downloaded from the OCS web site, and was horizontally referenced to NAD 83 geographic and vertically referenced to MLLW (meters). The data were transformed to MHW using a constant offset and were reviewed and compared to the coastline and to the corresponding RNCs.
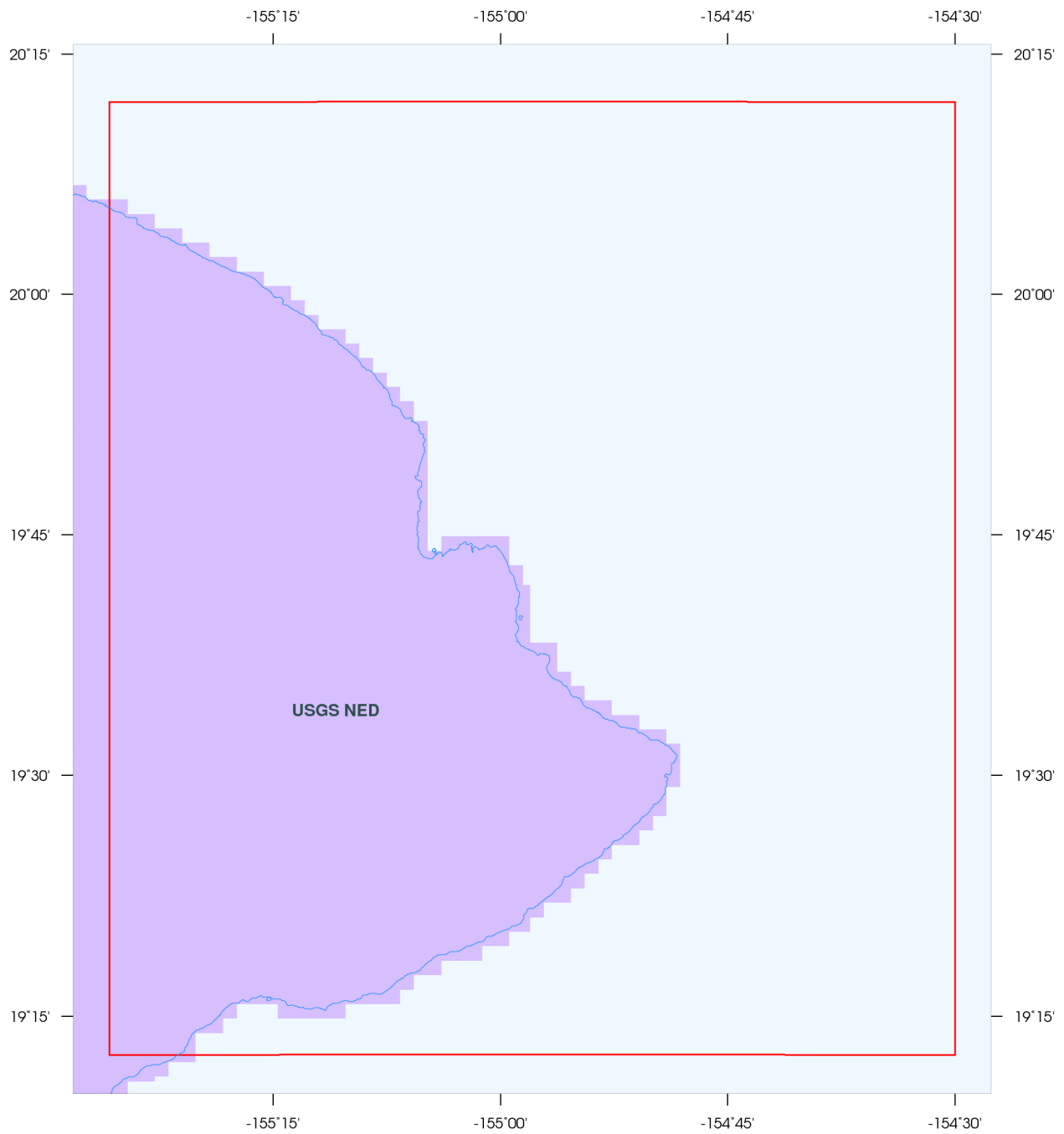
3.1.3   Topography

The topographic dataset used to build the Hilo DEM was the US Geological Society (USGS) National Elevation Dataset (NED) 1/3 arc-second DEM; (Table 4; Fig. 6).

Table 4. Topographic datasets used in compiling the Hilo DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
USGS	2011	Bare-earth DEM	1 - 5 meters	WGS 84 geographic	Assumed MSL (meters)	N/A

1) USGS NED 1/3 arc-second DEM

The USGS NED provides complete 1/3 arc-second coverage of the Hawaiian Islands. Data are in NAD 83 geographic coordinate and assumed MSL vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov). The dataset was derived from USGS quadrange maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999. The NED DEMs were transformed to NAD 83 and MHW using a constant offset (Table 5). The gridded data were evaluated and positive elevations over open water were removed by clipping the data to the coastline using *GDAL* and *Python*. The resulting data were converted to *xyz* data using *GDAL*.

Figure 6. *Topographic data source in the Hilo region.*

3.2   Establishing Common Datums

3.2.1   *Vertical Datum Transformations*

Datasets used in the compilation and evaluation of the Hilo DEM were originally referenced to several vertical datums including MLLW and MSL. All datasets were transformed to MHW using constant offsets obtained from tidal gauges at Hilo Bay.

- **Bathymetric Data:** All hydrographic surveys were transformed from MLLW or MSL to MHW using a constant offset based on the relationship shown in table 5.

- **Topographic Data:** All topographic datasets used in the compilation of the Hilo DEM originated in MSL vertical datum and were transformed to MHW using a constant offset based on the relationship shown in table 5.

Table 5. Relationship between MHW and other vertical datums in the Hilo Bay region, determined using station 1617760

Vertical Datum	Difference to MHW
MSL	-0.350520 meters
MLLW	-0.731520 meters

3.2.2   *Horizontal Datum Transformations*

Datasets used to build the Hilo DEM were downloaded or received referenced to WGS 84 geographic or NAD 83 geographic horizontal datums. The relationship transformational equations between these horizontal datums are well established. Data were transformed to a horizontal datum of NAD 83 geographic using *Proj4*.[3]

3.3   Verifying consistency between datasets

After horizontal and vertical transformations were applied, the ascii *xyz* files were reviewed for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps.

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[3]*Proj4* is a free standard Unix filter function which converts geographic longitude and latitude coordinates into cartesian coordinates, $(\lambda, \phi) \rightarrow$(x, y), by means of a wide variety of cartographic projection functions. http://trac.osgeo.org/proj/

4. DEM DEVELOPMENT

4.1 Smoothing of bathymetric data

The NGDC multibeam hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Hilo DEM. This is especially true for deep water surveys in the Pacific and shallow water surveys in bays where data have point spacing up to 350 meters apart. In order to reduce artifacts created in the DEM by the low-resolution bathymetric datasets, and to provide effective interpolation in the deep water and into the coastal zone, a 1/3 arc-second-pre-surface bathymetric grid was generated using Generic Mapping Tools (GMT)[4]. The coastline elevation value was set at 0 meters to ensure a bathymetric surface below zero in areas where data are sparse or non-existent.

The point data were median-averaged using the GMT command "blockmedian" to create a 1/3 arc-second grid 0.05 degrees (∼5%) larger than the Hilo DEM gridding region. The GMT command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The GMT grid created by 'surface' was converted to an ESRI Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation onto land areas) using GDAL. The resulting surface was exported as an *xyz* file for use in the final gridding process (Table 6).

4.2 Building the MHW DEM

MB-System[5] was used to create the 1/3 arc-second Hilo DEM. The MB-System command 'mbgrid' was used to apply a tight spline tension to the *xyz* data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 6. The resulting binary grid was converted to an Arc ASCII grid using the MB-System tool 'mbm_grd2arc' to create the final 1/3 arc-second Hilo DEM. Figure 7 illustrates cells in the DEM that have interpolated values (shown as white) versus data contributing to the cell value (shown as black).

Table 6. Data hierarchy used to assign gridding weight in MB-System

Dataset	Relative Gridding Weight
USGS NED	100
NGDC Multibeam	10
OCS ENC	10
Pre-surfaced bathymetric grid	1

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[4]GMT is an open source collection of ∼60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ∼30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.]

[5]MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (point and access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994–1997), NOAA (2002–2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from MB-System web site.]
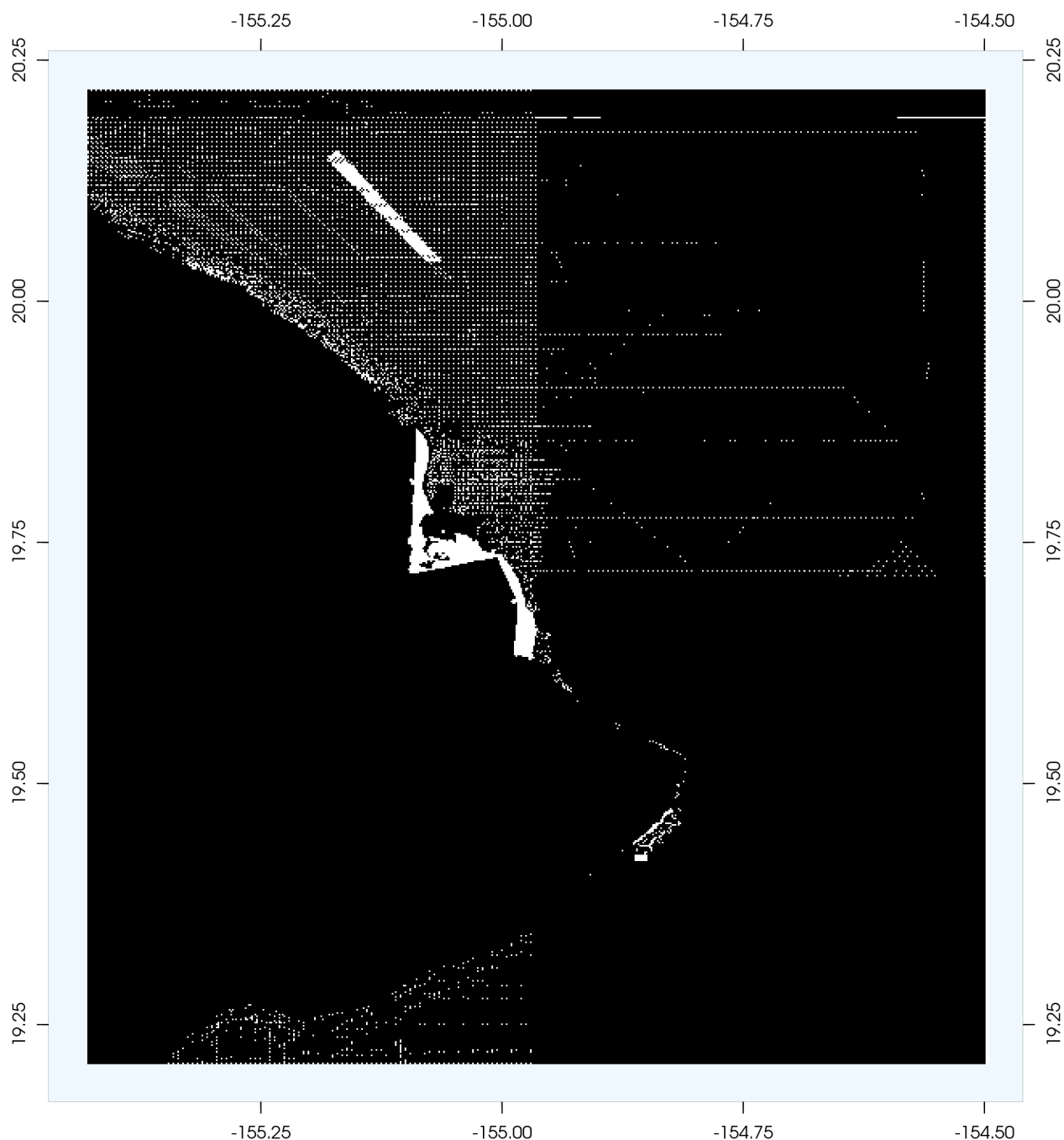
Figure 7. *Data density of the Hilo gridding region; Areas where source data were available are depicted in black; areas where grid interpolation was necessary are depicted in white. Areas of sparse data density are difficult to see at the current scale.*

4.3   Quality Assessment of the structured DEM

4.3.1   *Horizontal accuracy*

The horizontal accuracy of topographic and bathymetric features in the Hilo DEM is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM, making the highest accuracy possible 1/3 arc-seconds (about 10 meters). The horizontal accuracy is 10 meters where topographic lidar datasets

contribute to the DEM cell value. The horizontal accuracy is 0.75 meters at 1 sigma where bathymetric–topographic lidar-derived data contributes to the DEM cell value. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub aerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; and by the morphologic change that occurs in this dynamic region.

### 4.3.2 *Vertical accuracy*

Vertical accuracy of the Hilo DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic lidar has an estimated RMSE of 13.9 to 20 cm. Topographic data has an estimated RMSE of 7 to 15 meters or better in areas of unobstructed flat ground. Bathymetric-topographic lidar-derived data have a vertical accuracy of 0.20 meters at 1 sigma. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys.

4.3.3 *Slope maps and 3D perspectives*

GMT was used to generate a slope grid from the Hilo DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figure 8). The DEM was transformed to projected coordinates (horizontal units in meters) using GMT for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 9 shows a perspective view image of the 1/3 arc-second Hilo in its final version.
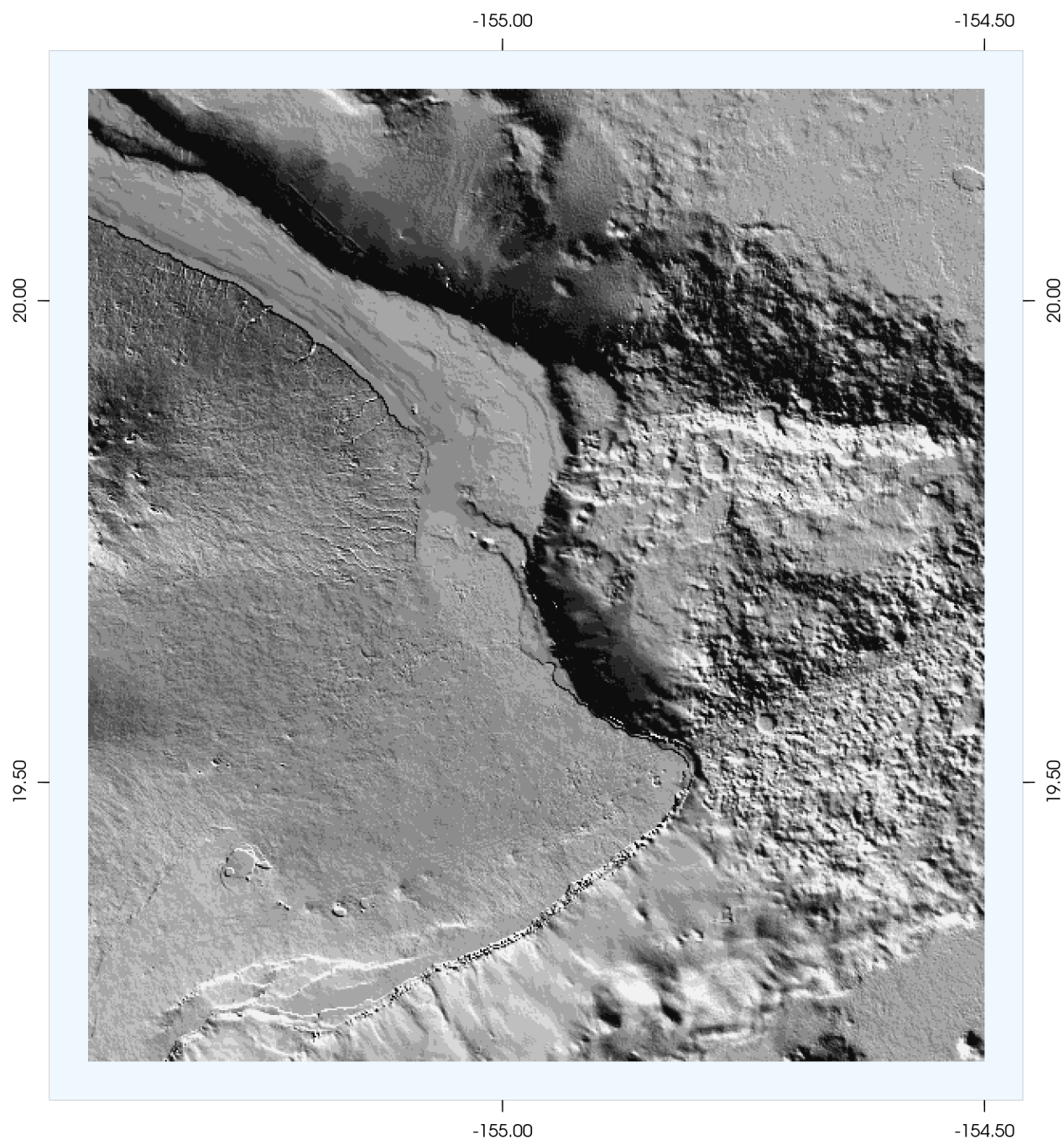
Figure 8. *Slope map of the Hilo DEM. Light shading denotes flat-lying slopes; dark shading denotes steep slopes.*
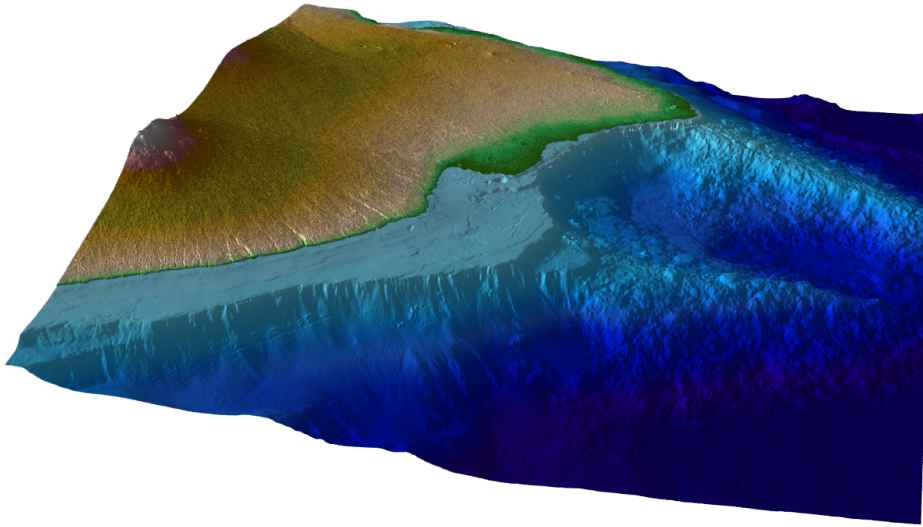
Figure 9. *Perspective view from the northwest of the Hilo DEM. Two times vertical exaggeration.*

4.3.4 Comparison with NGS geodetic monuments

The elevations of 21 NOAA National Geodetic Survey (NGS) geodetic monuments (Figure 10) were extracted from online shapefiles of NGS geodetic monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monument elevations were transformed to MHW using a constant offset and were compared with elevations in the Hilo DEM. Differences between the DEM elevations and the NGS geodetic monument elevations range from -39.2307 to 40.775 meters, with the majority of them being within +/-1 meter (Figure 11). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of an observation tower, light house or at the apex of other structures.
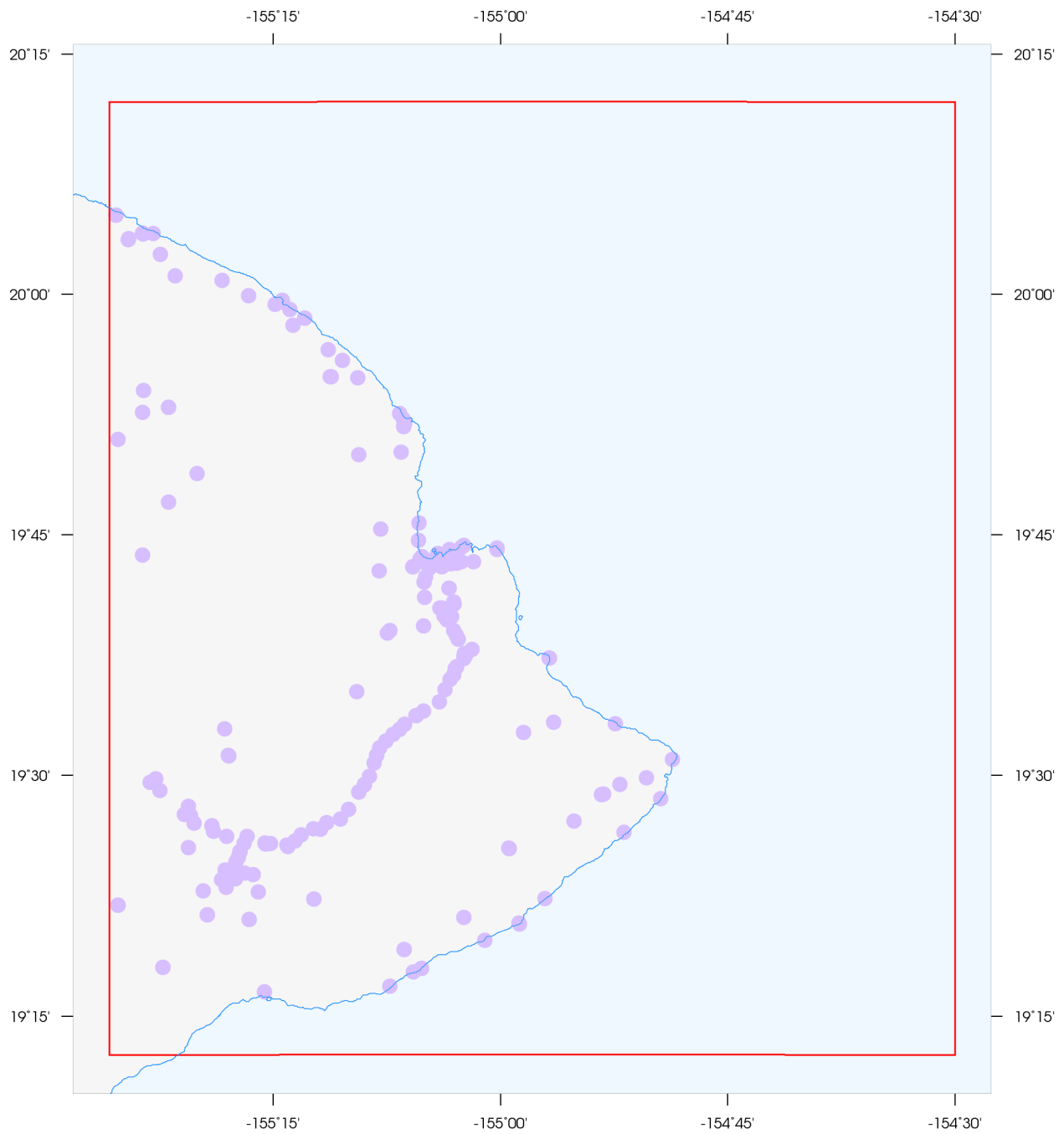
Figure 10. *Locations of NGS monuments used in the evaluation of the Hilo DEM.*
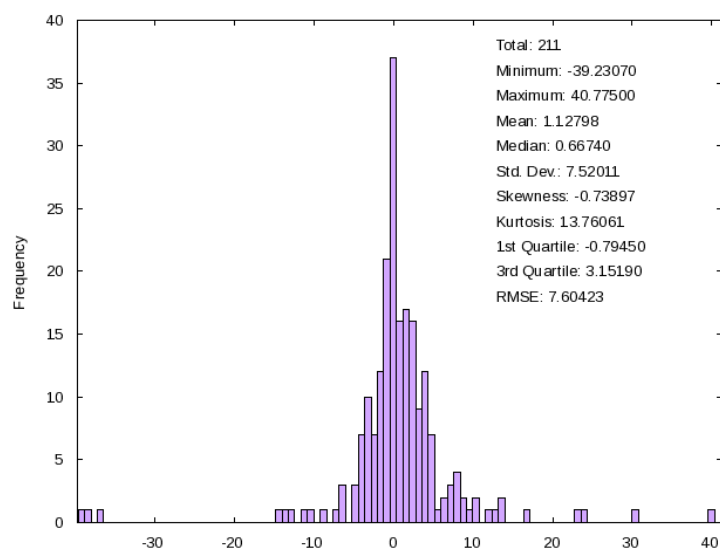
Figure 11. *Histogram of the differences between the NGS monument elevation values and the Hilo DEM*

5. SUMMARY AND CONCLUSIONS

A bathymetric–topographic structured digital elevation model of the Hilo, HI region, with cell spacing of 1/3 arc-second, and a vertical datum of MHW was developed by NGDC for PMEL for use in tsunami generation, propogation and inundation simulations.

Recommendations to improve the Hilo DEM, based on NGDCs research and analysis, are listed below:

- Conduct publically available lidar surveys of all topographic regions.

6. ACKNOWLEDGEMENTS

The creation of the Hilo DEM was funded by NOAA PMEL. The authors thank Nazila Merati, Marie Eble and Vasily Titov (PMEL).

7. REFERENCES

Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A, 2003. Federal Emergency Management Agency, Flood Hazard Mapping Program.

8. DATA PROCESSING SOFTWARE

ArcGIS 10, developed and liscensed by ESRI, Redlands, California, http://www.esri.com

ESRI World Imagery - ESRI ArcGIS Resource Centers, http://www.esri.com

GEODAS v. 5 - Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas

GMT v. 4.1.4 - Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com

GDAL v. 1.8.0 Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org

Proj4 v. 4.7.0 free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/

VDatum v. 2.3 developed and maintained by NOAAs National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/